FORCE TRANSFER MECHANISMS AND SHEAR STRENGTH OF REINFORCED CONCRETE BEAM-COLUMN ELEMENTS

Wu-Wei Kuo 1, Shyh-Jiann Hwang 2, and Ying-Zhi Chen 3

ABSTRACT

This paper studies the force transferring mechanisms and shear strength of reinforced concrete (RC) beams. The transferring mechanism of shear forces in RC beams can be characterized as the load paths in the disturbed regions and the beam regions. The domains of different regions are proposed to be determined by the beam geometry, the longitudinal and transverse reinforcement. The inclination angles in each region are defined according to the proposed load paths of the force transferring. The disturbed regions are failed due to shear compression failure and shear tension failure. The failure mode of the beam region is shear tension failure. The shear tension failure is the yielding of shear reinforcement and the shear compression failure is the diagonal crushing of concrete. The shear strength due to the shear compression failure can be predicted by the softened strut-and-tie model, and the shear tension failure can be calculated according to the ACI 318-05 code approach. Accuracy of the proposed model is gauged by comparing with the available test data. Finally, the proposed model of beams is applied to columns.

Keywords: Discontinuities, Force transfer, Reinforced concrete, Shear, Strength

INTRODUCTION

Various behavioral models have been proposed for predicting the shear strength of RC beams. The truss model, originally introduced by Ritter (1899) and Mörsch (1909) at the turn of the 19th century, has been provided an excellent basis for design of shear steel. The structural action can be represented by a truss, with the main steel providing the tension chord, the concrete top flange acting as the compression chord, the stirrups providing the vertical tension web members, and the concrete between inclined cracks acting as compression diagonals. Furthermore, the truss analogy method has been greatly extended by the recent work of Schlaich et al. (1987) and also was contained in the texts by Collins and Mitchell (1991) and MacGregor (1997), and referred as strut-and-tie model. In a RC structure, the member is classified as either B- (Beam or Bernoulli) Regions or D- (Disturbed or Discontinuity) Regions. B-Regions are parts of a structure in which Bernoulli's hypothesis of straight-line strain profiles applies. D-Regions, on the other hand, are parts of a structure with a complex variation in strain. D-Regions include portions near abrupt changes in geometry (geometrical discontinuities) or concentrated forces (static discontinuities). St. Venant's principle suggests that a local disturbance such as a concentrated load will dissipate within about one beam depth from the applied point, as shown in Fig. 1. Also this concept is included in ACI 318-05 Appendix A (2005). However, St. Venant principle is only applied in elastic material without cracking. In fact, the

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reinforcement becomes active and redistribution of internal stresses occurs after concrete cracks. Under this circumstance, the division between B- and D-region should not follow the simple rule of one section depth from the discontinuity. It should be a function of the concrete strength, main reinforcement, shear reinforcement, ... etc. If the division between B- and D-region can be defined clearly, more accuracy can be obtained in predicting the behavior for RC beams and columns.

In this paper the force transferring mechanisms and shear strength of reinforced concrete beams are proposed based on the work of MacGregor (1997). Also, an analytical model for shear strength prediction is developed, followed by experimental verifications. Finally the proposed model of beams is applied to columns in order to demonstrate the capability and reliability of proposed method.

THE SHEAR TRANSFERRING MECHANISMS AND FAILURE MODES OF BEAMS


According to Commentary of ACI 318-05 Appendix A (2005), D-region includes the portion of a member within a distance, h, from a force discontinuity or a geometry discontinuity, as shown in Fig. 1. If two D-regions overlap or meet as shown in Fig. 2, they can be considered as a single D-region for design purposes. The maximum length-to-depth ratio of such a D-region would be approximately two. Thus, the smallest angle between the strut and the tie in a D-region is \( \arctan \frac{1}{2} = 26.5 \) degrees, rounded to 25 degrees. The strut-and-tie method is emerging as a code-worthy methodology for the design of D-Regions in structural concrete. If there is a B-region between the D-regions in a shear span, as shown in Fig. 2, the strength of the shear span is governed by the strength of the B-region if the B- and D-regions have similar geometry and reinforcement (ACI Committee 318, 2005). This is because the shear strength of a B-region is less than the shear strength of a comparable D-region. Shear spans containing B-regions are designed for shear using the traditional shear design procedures ignoring D-regions.

Proposed Method

The truss analogy was proposing independently by Ritter (1899) and Mörch (1909) in the early 1900s for shear design of RC beams. In 1997, MacGregor suggested that the truss model is one of the best analytical model for shear design. The construction of a plastic truss model can be illustrated by example in Fig. 3. The vertical applied load, V, must be transmitted by diagonal compression strut (shown by dashed inclined lines) to enough stirrups (shown by solid vertical lines) to equilibrate this force. The stirrup transmits the vertical force to the top joint of the truss, where it is resisting by the vertical component of the force in diagonal strut, and so on.

The compression diagonals originating at the load are referred to as a compression fan. It can be found in Fig. 3 that each of the compression fans occurs in regions of concentrated load as well as in both end supports. Between the compression fans is a compression field consisting of the parallel diagonal
struts. The compression fan occurs in a D-region, whereas the compression field is a B-region. For the D-region where the flow of stresses is non-uniform, the strut-and-tie model (MacGregor, 1997; Collins and Mitchell, 1991) may be used to determine internal force effects. And for the B-region the smeared concrete model may be used because of state of uniform stresses (Hsu and Mo, 1985). The strains can meet the requirement of Mohr’s compatibility in both D- and B-regions. The softening phenomenon of concrete is also taken into account by the laws of constitutive.

However, not all the flow of force in a cracked concrete beam go through D-, B-, then D-region as mentioning above. It is believed that a force flow of a single D-region is possible in a deep beam with a ratio of shear span to effective depth \( \frac{a}{jd} \) of 2.0 or less (Fig. 4). The length \( jd \) is the lever arm from tensile reinforcement to the center of compression stress. For beams with ratio of \( a/jd \) more than 2.0, the path transferring load to the support passes through both B- and D-regions, as shown in Fig. 4. To account for the influence of the steel reinforcement location, the ratio of shear span to effective depth \( \frac{a}{jd} \) is used instead of \( a/d \) in this paper.

For a deep beam with ratio of \( a/jd \) of 2.0 or less, the strut-and-tie model is used to evaluate the shear strength and failure mode because of the non-uniform stresses state all over the beam. In this paper, the softened strut-and-tie model developed by Hwang et al. (2000, 2002) is adopted to account for the force transferring mechanism in D-region. The shear failure of a single D-region is set to a crushing of
concrete in a diagonal compression strut, and it is referred to as shear compression failure ($V_{DC}$) in this paper.

For an ordinary beam with ratio of $a / jd$ more than 2.0, the flow of internal force transmitted through D-region, via B-region, and then to D-region, instead of D-region only. When force flows from D-region to B-region, the stresses state would change from non-uniform to uniform. The failure mode of the B-region is diagonal tension failure ($V_{BT}$) due to yielding of stirrups. The first cracking angle, $\alpha$, is 45 degrees under uniform stresses without axial load. The shear strength can be predicted by modified truss analogy (ACI Committee 318, 2005).

On either side of the B-region is the D-region with disturbed stresses. The ACI code (2005) defines a D-region as a function of a member within a distance, $h$, from a force discontinuity or a geometry discontinuity. In theory, this D-region definition works only on linear elastic materials based on St. Venant's principle. For reinforced concrete structures, a more rational approach to deive B- and D-region will lead to a better prediction. In fact, parameters such as reinforcement, stirrups, and concrete strength are supposed to correlate closely with the extent of the D-region. According to the concept of MacGregor (1997), the vertical applied load, $V$, is transmitted by diagonal compression struts to enough stirrups to equilibrate this force vertical load (Figs. 3 and 5). The compression struts and tension ties are interconnected at nodes in equilibrium state (Fig. 5). Therefore, parameters like concrete strength, reinforcement strength and layout...etc will affect the equilibrium at nodes. That is, the stronger the shear $V$ is applied, the more nodes are needed to maintain equilibrium state. The quantities of nodes for equilibrium can be determined by Eq. 1. When estimating the value of $n$ in Eq. 1, the value of shear should be less than $V_{mn}$ and $V_{BT}$, in which $V_{mn}$ is the shear strength when nominal moment $M_n$ reaches. The value of $V_{BT}$ is the shear strength with diagonal tension failure in B-region, also it is the nominal shear strength $V_n$ according to ACI 318-05 code (2005). The effectiveness of shear reinforcement within D-region was proposed by Hwang and Lee (2002). In Eq. 2, $\theta$ stands for angle of inclination of the diagonal compression with respect to the horizontal axis. As shown in Figs. 5 and 6, the width of D-region can be determined by horizontal distance between the point of applied load and the center of resultants of all nodes in D-region.

![Figure 5. Shear transferring mechanism in D-region](image)

![Figure 6. D-region](image)

\[
n = \frac{V_{\text{lim}}}{A_s f_{vy}} \tag{1}
\]

\[
\theta = \tan^{-1}(jd / \ell_h) \tag{2}
\]

In these equations above, $V_{\text{lim}}$ is the minimal of $V_{BT}$ and $V_{mn}$, $n$ is the number of nodes to maintain equilibrium, $A_s$ is area of shear reinforcement, $f_{vy}$ is yield strength of shear reinforcement, $\theta$ is angle of average principal stress of concrete, $\ell_h$ is the internal lever arms of the shear couples.

It can be found in Eq. (1) : if $V_{\text{lim}}$ gets larger or $A_s f_{vy}$ is smaller, more stirrups will be needed to resist $V_{\text{lim}}$, then the area of D-region will extend and the $\theta$ angle becomes mild. According to Thürlimann...
The shear cracks in beams are at an angle between 26.5 and 63.5 degrees. As a result, the angle of principal stress of concrete is assuming between 26.5 and 63.5 degrees, also this assumption is similar to the definition of ACI 318-05 (2005).

The D-regions of a deep beam and an ordinary beam are both the areas of disturbed stresses, but they have different shear transferring mechanisms. In the D-region of a deep beam, as the internal force is transmitted directly from the point of concentrated load to the support, the either end of this concrete strut is stress-concentrated and well-supported. On the other hand, in the B-region of an ordinary beam, the concentrated compressive stresses at the point of the concentrated load are transmitted by some struts and ties to get equilibrated. If the equilibrium of struts and ties is maintained, and there is enough shear reinforcement to resist internal stresses, then the concrete struts may be crushed before the shear reinforcement yields. The failure mode is shear compression failure in D-region ($V_{DC}$). As the shear load $V$ gets higher, the area of D-region will be larger. If more nodes are needed to equilibrate the shear load $V$, the angle $\theta$ will become smaller, and the cracking width will become larger. At this time, the stiffness of this region is too week to develop a strut-and-tie force transferring mechanisms. Therefore, the shear reinforcement tends to yield before the concrete struts get crushed. The failure mode is diagonal tension failure in D-region ($V_{DT}$). The angle of diagonal tension cracking is assumed $\beta = 26.5^\circ$, and the shear strength is estimated by the internal forces equilibrated along the crack. However, the proposed $\beta$ (26.5°) represents the main crack angle of diagonal tension failure in D-region, not the angle of principal stress in D-region.

**PREDICTIONS OF SHEAR STRENGTH**

**Shear Strength for Concrete with Shear Compression Failure in D-region ($V_{DC}$)**

For predicting the shear strength for concrete with shear compression failure in D-region, the softened strut-and-tie model (Hwang and Lee, 2002) may be used. In this model, the complex flow of internal forces in the D-Region under consideration is idealized as a truss carrying the imposed loading through the region to its supports. Also this model satisfies the requirement of compatibility and the softening phenomenon of concrete. A simplified softened strut-and-tie method, proposed by Hwang and Lee (2002), was developed for engineering use. Based on the simplified method, the diagonal concrete compression $C_d$ and shear strength $V_{DC}$ for concrete with shear compression failure in D-region can be defined:

$$V_{DC} = C_d \sin \theta = K \zeta f'_c A_{sr} \sin \theta$$

in which $K$ is strut-and-tie index, a factor representing the beneficial effect of the tie force on the shear strength; $\zeta$ is the softening coefficient; $f'_c$ is compressive strength of concrete. The effective area of the diagonal strut $A_{sr}$ in D-region is defined as

$$A_{sr} = a_s \times b_s$$

where $a_s$ is depth of the diagonal strut; and $b_s$ is width of the diagonal strut, that is, the width of beam. The effective depth $a_s$ are decided by the depth of compression zone $a_b$ and the width of support plate $a_p$.

$$a_s = \sqrt{a_b^2 + a_p^2}$$

in which $a_b$ equals to $kd$, and coefficient $k$ could be referred to Hwang et al. (2000).
On the other hand, $V_{DC}$ decreases as the ductility of member increases. This does not include in present study.

**Shear Strength with Diagonal Tension Failure in B-region ($V_{BT}$)**

As for the prediction of $V_{BT}$, the equation in ACI 318-05 code (2005) are modified and adopted as follows:

$$V_{BT} = V_c + V_s = \left( \sqrt{f'_c} + 120 \rho_w \frac{V_{yd}}{M_u} \right) \frac{bd}{s} + A_v f_{ty} \frac{jd \cot \alpha}{s}, \text{ in MPa}$$

in which $V_c$ denotes nominal shear strength provided by concrete due to aggregate interlock; and $V_s$ is nominal shear strength provided by vertical shear reinforcement; $\rho_w$ is ratio of tension reinforcement; $V_{yd}$ is design shear force at section; and $M_u$ is design moment at section; $A_v$ is area of shear reinforcement within a spacing $s$; $f_{ty}$ is yield strength of shear reinforcement; $\alpha$ is an angle of 45 degrees.

**Shear Strength with Diagonal Tension Failure in D-region ($V_{DT}$)**

As the force transferring mechanism mentioned above, stirrup plays an important role in nodal equilibrium. Since the angle of inclined cracks is not less than 26.5 degrees, the diagonal tension failure could happen if there are not enough stirrups in D-region. The prediction of shear strength $V_{DT}$ is similar to that of $V_{BT}$. The only modification is the calculation of $V_s$ because the angle of $\beta$ is 26.5 degrees, rather than 45 degrees.

$$V_{DT} = V_c + V_s = \left( \sqrt{f'_c} + 120 \rho_w \frac{V_{yd}}{M_u} \right) \frac{bd}{s} + A_v f_{ty} \frac{jd \cot \beta}{s}$$

**EXPERIMENTAL VERIFICATION**

The estimations of the proposed method are compared with the 206 specimens tested by ACI-ASCE Committee 326 (1962) coming from Moretto (1945), Clark (1951), Moody et al. (1954, 1955), Rodriguez et al. (1959), Elstner et al. (1955), as well as other related references (Mphonde, 1984; Elzanaty et al., 1986; Johnson and Ramirez, 1989; Roller and Russell, 1990; Sarsam and Al-Musawi, 1992; Xie et al., 1994; Kong and Rangan, 1998). As listed in Table 1, specimens of rectangular section with vertical or inclined shear reinforcement are included. The failure modes of all specimens must be either shear compression failure or diagonal tension failure. To ensure each specimen being shear failure, the flexure strength is calculated in advanced and compared with shear strength of test results. Besides, the strength reduction factor is taken as unity as the dimensions and material properties of all specimens are known.

Accuracy for the proposed procedures is gauged in terms of a strength ratio, which is defined as the ratio of the measured to the computed strengths. The detailed experimental verifications are shown in Table 1 and Fig 7. For deep beams with $a/jd$ of 2.0 or less, the softened strut-and-tie model suggested by Hwang and Lee (2002) are used to predict the shear strength (Eq. 3). The average strength ratio for these members is 1.17, and the coefficient of variation is 0.20. And for the beams with $a/jd$ more than 2.0, the average strength ratio for these members is 1.38, and the coefficient of variation is 0.24. Almost all the longer beams are diagonal tension failure except two specimens are shear compression failure. As shown in Fig. 7, for the cases of $a/jd$ between 2.0 and 3.0, the predictions of the proposed method are more conservative than those of $a/jd$ between 3.0 and 5.0.
The average strength ratios are 1.52 and 1.23 respectively. According to ACI code (2005), a member with B-regions, and the geometrical and reinforcement configurations similar to D-regions, the strength of B-regions will govern and become diagonal tension failure. This point of view agrees with that from experimental verifications. However, the definition of D-region in about one beam depth will cause an incomplete load path within B-regions in beams of \(a/\text{jd}\) between 2.0 and 3.0. It might be conservative to design such members using B-regions with concrete diagonal tension failure according ACI code (2005). As spans of members get longer, a complete B-region can exist in the member, and the predictions and the test results tend to agree with each other. On the other hand, defining D-regions using proposed method leads to another result, as shown in Fig. 8.

### Table 1 Test data of 206 specimens

<table>
<thead>
<tr>
<th>Author</th>
<th>No.</th>
<th>(a/\text{jd})</th>
<th>(f'_c) MPa</th>
<th>(\rho_s)%</th>
<th>(V_{\text{test}}/V_{\text{calc}})</th>
<th>Avg.</th>
<th>Cov.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moretto (1945) [12]</td>
<td>13</td>
<td>1.90-2.15</td>
<td>19.69-33.13</td>
<td>0.28-0.74</td>
<td>1.64</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Clark (1951) [13]</td>
<td>42</td>
<td>1.36-2.95</td>
<td>13.79-47.58</td>
<td>0.34-1.22</td>
<td>1.19</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Moody et al. (1954)</td>
<td>2</td>
<td>1.82-1.83</td>
<td>22.41-25.37</td>
<td>0.52-0.95</td>
<td>1.10</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Rodriguez et al. (1959) [15]</td>
<td>13</td>
<td>1.55-4.64</td>
<td>20.13-35.31</td>
<td>0.37-2.22</td>
<td>1.23</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Elsner et al. (1955)</td>
<td>31</td>
<td>1.75-4.81</td>
<td>18.89-35.37</td>
<td>0.52-2.14</td>
<td>1.33</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Mphonde (1984) [17]</td>
<td>20</td>
<td>4.16-4.24</td>
<td>22.08-82.95</td>
<td>0.12-0.38</td>
<td>1.24</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Elzanaty et al. (1986) [18]</td>
<td>3</td>
<td>4.66-4.73</td>
<td>20.69-62.47</td>
<td>0.19</td>
<td>1.31</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Johnson and Ramirez (1989) [19]</td>
<td>6</td>
<td>3.56-3.61</td>
<td>36.40-72.33</td>
<td>0.08-0.16</td>
<td>1.00</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Roller and Russell (1990) [20]</td>
<td>10</td>
<td>2.80-3.46</td>
<td>72.40-125.00</td>
<td>0.07-1.77</td>
<td>1.07</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Sarsam and Al-Musawi (1992) [21]</td>
<td>14</td>
<td>2.87-4.72</td>
<td>39.00-80.10</td>
<td>0.09-0.19</td>
<td>1.85</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Xie et al. (1994) [22]</td>
<td>9</td>
<td>1.16-4.74</td>
<td>40.27-103.22</td>
<td>0.49-0.79</td>
<td>1.34</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Kong and Rangan (1998) [23]</td>
<td>43</td>
<td>2.79-3.92</td>
<td>63.60-89.40</td>
<td>0.10-0.26</td>
<td>1.44</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>206</td>
<td>1.16-4.84</td>
<td>13.79-125.00</td>
<td>0.07-2.22</td>
<td>1.34</td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 7. Experimental verifications](image)

In Fig. 8, the horizontal axis of \((a-2D)/\text{jd}\) is an index to evaluate B-regions existing in a member or not. D denotes length of D-regions. In case \((a-2D)/\text{jd}\) small than 0, there is no B-region in this member. If \((a-2D)/\text{jd}\) is between 0 and 1, there is an incomplete B-region in the member. If \((a-2D)/\text{jd}\) is larger than 1, there are both B- and D-regions in the member. As shown in Fig. 8, as B-region becomes more complete, the test results can get closed to the predictions of diagonal tension strength according to ACI code (2005). But for the members without B-regions, it is much more conservative to use the same predictions of diagonal tension strength. Based on the proposed transferring mechanism, shear reinforcement equilibrates internal forces at nodes. Once the shear reinforcement is not enough, it may cause the angle of compression struts becomes 26.5 degrees.
Along with the length of the member is too short, two D-regions will overlap. As a result, the diagonal tension failure \( V_{DT} \) will happen. In predicting the shear strength using diagonal tension strength in D-region, the coefficient of variation is still high but closing to test results. It is recommended to use diagonal tension strength in D-region to predict the shear strength of members without B-regions. However, some unconservative prediction by the proposed model shows that the main crack angle of diagonal tension failure is not necessary 26.5 degrees; therefore, the determination of \( \beta \) could be modified.

![Figure 8. Experimental verifications](image8)

![Figure 9. Different types of columns](image9)

![Figure 10. Force transfer mechanism of column](image10)

**The Transferring Mechanism of Shear Forces and Failure Modes in RC Columns**

The shear transferring mechanism in columns is similar to that in beams. The study suggests that it may use a single D-region in a very short column with a ratio of shear span to effective depth \( a/jd \) of 2.0 or less (Fig. 9). For a short or slender column with ratio of \( a/jd \) of more than 2.0, the path transferring load to the support passes through both B- and D-regions, as shown in Fig. 9. The failure mode of a very short column is shear compression failure in D-region, and the shear strength \( V_{DC} \) is calculated using the model proposed by Hwang and Lee (2002). However, in calculating the effective area of the diagonal strut \( A_{sr} \) in the very short column, the influence of axial load should take into account. On the other hand, for the columns with both B- and D-regions, the force transferring mechanisms are similar to those of ordinary beams. Tension ties (stirrups) and concrete struts transmit the lateral loads to center of the column (Fig. 10). Close to both ends of the column are D-regions, and between the D-regions is the B-region. The failure mode of D-regions is diagonal tension \( V_{DT} \) or
diagonal compression \( (V_{DC}) \) failure. The predictions of shear strength are the same as beams except for the calculations of \( A_{DC} \), \( V_c \) (Eq. 8) and \( V_{mn} \) due to axial loads. The failure mode of the B-regions in columns is diagonal tension \( (V_{BT}) \) failure. The first cracking angle, \( \alpha \), is no longer 45 degrees and can be computed by Eq. 9 proposed by Chen (2006).

\[
V_c = 0.167(1 + \frac{N_u}{14A_g})\sqrt{f_{c}bd}
\]

\[
\alpha = 45^\circ + \frac{1}{2}\left(\tan^{-1}\left(\frac{\sigma}{2f_r \cdot \sqrt{1 + \sigma/f_r}}\right)\right)
\]

in which \( N_u \) is axial force applied in columns, \( A_g \) is gross area of column section, \( \sigma \) is compressive stress of columns \( (\text{kgf/cm}^2) \), and \( f_r \) is allowable tensile stress of concrete \( (\text{kgf/cm}^2) \).

**CONCLUSIONS**

The shear transferring mechanisms and predictions of shear strength of reinforced concrete beams are proposed in this paper. According to the available test results in the literature and their comparison with the proposed model, the following conclusions can be made:

1. The definition of D-regions should consider the geometrical and reinforcement configurations of reinforced concrete structures. The formula expresses explicitly the contributions of the shear reinforcement, concrete strength with softening effect, and cross sectional area of strut. According to the ACI code provisions (2005), D-regions are related only to the depth of members. The proposed Eqs. 1 and 2, related with shear reinforcement, concrete strength, and geometry of elements, are recommended for predicting the D-regions.

2. The stresses in D-regions are disturbed. If there is enough shear reinforcement provided, the shear strength in D-region will be the diagonal compression strength \( (V_{DC}) \). If not, the diagonal tension failure \( (V_{DT}) \) along with inclined cracks would happen. The angle of inclined cracks is proposed as \( \beta = 26.5^\circ \). Eq. 7 is recommended for predicting the diagonal tension strength in D-regions.

3. The stresses in B-regions are uniform. The state of node equilibrium could be described by the smeared concrete model. Eq. 6 is recommended for predicting of diagonal tension strength. The first cracking angle, \( \alpha \), equals 45 degrees for beams, and uses Eq. 9 for columns.

4. The method proposed herein was compared with 206 specimens available in the literature, and satisfactory correlation was found

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